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Small satellite radiation budget instrumentation

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ABSTRACT

A major diagnostic in understanding the response of the Earth's climate to natural or anthropogenic changes is the radiative balance at the top of the atmosphere. Two classes of measurements may be undertaken: (1) a monitoring of the radiation balance over decade-long long time-scales, and (2) measurements designed to provide a sufficiently complete data set to validate or improve models. This paper discusses some of the important ingredients in obtaining such data, and presents a description of some candidate instrumentation for use on a small satellite.

1. INTRODUCTION

The highest priority near-term scientific and policy-related issue for the U. S. Global Change Research Program (USGCRP)¹ is to understand the anthropogenic effects on the climate. It is recognized *a priori*, that the climate is affected greatly by many factors, most notably the effects of water vapor and clouds, and the interaction of the oceans and atmosphere. Furthermore, local phenomena may have consequences for the earth as a whole.

This is a non-linear problem with many variables on a variety of spatial and temporal scales. Clearly it would be desirable to measure all of the relevant parameters to high accuracy and with full spatial and temporal coverage, and then to use that information in models with sufficient physics content to gain a predictive capability. In reality, both observations and modeling currently fall short of this ideal. For example, the radiative balance at the top of the atmosphere was measured by the Earth Radiation Budget Experiment (ERBE) with a series of three satellites carrying several broad-band radiometers, starting on the ERBS satellite in October, 1984. (See Refs. 2,3 and references therein for details on ERBE). The last data from the ERBE scanning instruments was received in February, 1990, and the follow-on experiment, CERES, is not scheduled for flight until the TRMM and EOS A1 missions in late 1997 and 1998. (One or more of the French / Russian SeaRAB radiometers⁴ may fly on METEOR-3 satellites in the intervening period.)

Sophisticated models of radiative transfer have been developed for climate applications, and afford more detailed physics insights into the problem^{5,6}. Three-dimensional General Circulation Models (GCMs) attempt to model radiative processes over the whole planet. The GCMs are limited by available computational resources to include only simplified physics for the important processes (so-called parameterizations). Comparisons of GCMs (e.g. Ref. 7) show significant variation in global climate sensitivity. Much of this variability is attributable to the treatment of clouds in these models. Indeed, clouds have two major effects: they provide a higher albedo, thus reflecting more incoming solar radiation, and they trap thermal radiation from below and reradiate to space at colder temperatures⁸. One notes that the net effect of clouds results from the difference of these two relatively larger effects, so that small changes in clouds may have significant effects. Further, observations during the 1987 El Nino show that the greenhouse effect there increases non-linearly with sea surface temperature; concomitant cirrus cloud formation then reduces the incoming solar radiation, acting as a “thermostat” (Ref. 9).

Comparisons have been made between model outputs and measurements of top-of-the-atmosphere radiances and fluxes. For example, Morcrette and Fouquart¹⁰, used data from colocated radiosondes and surface observations as inputs to radiation calculations to simulate the clear-sky long-wave radiances at the top of the atmosphere. Comparisons were then made to ERBE measurements, and, for clear sky conditions, showed agreement with a bias of $1.9 \text{ W} \cdot \text{m}^{-2} \cdot \text{Sr}^{-1}$, correlation coefficient of 0.93, an *rms* error of $3.5 \text{ W} \cdot \text{m}^{-2} \cdot \text{Sr}^{-1}$ and calculated variances which were 85 percent of the observed. However, for cloudy sky situations the comparison is much less satisfactory, with a computed outgoing longwave radiation of $261 \text{ W} \cdot \text{m}^{-2}$ compared to an observed $239 \text{ W} \cdot \text{m}^{-2}$.

2. EXPERIMENT DESIGN

At least two philosophies may be applied to increasing our knowledge of the earth radiation system. ERBE was a “global monitoring mission” with monthly regional averages of the TOA flux as its main data product¹¹; significant science insights resulted, including the “thermostat” hypothesis mentioned above. A second philosophy is to obtain a sufficiently complete set of measurements to allow testing of a model or hypothesis. It is worth reminding oneself of the steps required to define a viable test of a model or hypothesis: One first choses a particular model or hypothesis to be tested, which, in the present context may be a GCM, regional climate model, radiative transfer code, or a hypothesis such as the “thermostat” referenced above. One establishes the limitations of the model: for example, one may ask whether the assumptions and boundary conditions are reasonable. An understanding of the model leads to a definition of which physical quantities need to be measured and to what accuracy to perform a test of the model. One may divide these items into those which are essential (“needs”), and those which could be reasonably computed or assumed constant (“wishes”). One then examines possible instrumentation, both existing and new, and identifies possible other sources of obtaining relevant data. Some measurement techniques require significant modeling to obtain physical quantities of interest from measured signals: one needs to evaluate the impact of the modeling on the accuracy of the derived quantity. Clearly one wishes to avoid extrapolations, since again these involve invoking models or assumptions. Thus,

one needs to measure over as large a domain of space, time and measurement (e.g. wavelength) and physical parameters as is covered by the model to obtain a full test of the model. The volume of data is a possible limiter on obtaining full coverage: an overwhelming volume of data may include redundant and unnecessary information, and may discourage analysis. Resources of staff and equipment, and schedule considerations are other unavoidable boundary conditions. Based on examining these issues, one will undoubtedly require iteration to arrive at an experimental plan which both tests a model and which fits within the resource constraints.

As a specific example, we now consider a possible experiment to improve the understanding of atmospheric radiative forcing. The proposal is to measure the important atmospheric properties (temperature, humidity, cloud distribution and properties, major atmospheric constituents) and use these as inputs to a model which computes the radiances or fluxes at the TOA or at the satellite, for comparison to measurements of those quantities. The required accuracies may be estimated by considering the linear sensitivities of, for example, computed TOA fluxes to uncertainties in the measurements. Specifically, a 1-K error in temperature retrieval results in a $2\text{--}4\text{ W} \cdot \text{m}^{-2}$ change in TOA flux. Similarly, a twenty-percent error in humidity retrieval translates to $5\text{--}10\text{ W} \cdot \text{m}^{-2}$ in TOA long-wave flux. For clouds, a ten percent uncertainty in cloud fraction, or a 1-km uncertainty in the height of thick overcast leads to a $5\text{--}10\text{ W} \cdot \text{m}^{-2}$ uncertainty in TOA flux. Thus, taking state-of-the-art measurements of the atmospheric parameters and propagating the uncertainties linearly through a typical model would give a root-sum-of-squares variation of some $10\text{ W} \cdot \text{m}^{-2}$ in the computed TOA long-wave flux. Note that $\sim 10\text{ W} \cdot \text{m}^{-2}$ in long-wave TOA flux also represents state-of-the-art measurements. (One could do a similar computation for TOA radiances, or for some other diagnostic parameter.)

Unfortunately, the problem is likely to be non-linear... Thus, one needs to sample the multi-dimensional parameter space over sufficiently wide ranges to perform regressions between the atmospheric parameters and the diagnostic variable (TOA or satellite location flux or radiance).

3. EXISTING MEASUREMENTS

The list of measurement needs for radiative forcing diagnostics is quite lengthy, and the required accuracies to achieve a meaningful model test are at or near the state-of-the-art. We are interested here in examining a wide range of conditions, and on sufficiently large spatial scales to see the mesoscale effects. This drives one to examining large areas (100's of kilometers) simultaneously, which requires operations on a satellite.

Existing and planned capabilities for measurements relevant to the radiative forcing problem are described by Smith¹². Since clouds are the main modulators of the radiation field⁸, we clearly need measurement capabilities for temperature and humidity which will operate in the presence of clouds. This implies the need for microwave systems, which are found in the TIROS Operational Vertical Sounder (TOVS) and Defense Meteorological Satellite Program (DMS-P) instrument suites. These systems obtain temperatures with accuracies of 1-2K and humidities with *rms* errors of 20-40 percent within several vertical layers, with horizontal resolutions of 50-200 km at nadir and full horizon-to-

horizon coverage from near-polar orbits. Upgrades to these capabilities occur periodically. Since these microwave systems are relatively heavy and consume significant power, there is a great benefit to using these existing data rather than attempting to incorporate such instruments on a small satellite. The horizontal correlation lengths for temperature and humidity are quite long (typically hundreds of kilometers), so that one need not be especially close to TOVS or DMSP to use these data. Over land, one may gain additional temperature and humidity information from radiosondes, which are launched regularly.

We shall therefore assume that the small satellite need not provide temperature and humidity measurements. However, measurements of radiative properties show comparatively short spatial correlations, and need to be addressed directly with the instruments on board the small satellite.

4. SMALL SATELLITE MEASUREMENT NEEDS

Spectra of the radiation emitted by the earth-atmosphere system were measured by a high-resolution spectrometer aboard the Nimbus-III satellite some two decades ago¹³. These spectra covered the wavelength region from six to 25 μm , which covers some 60-75 percent of the outgoing longwave radiation (OLR) power. One readily observes that the spectra are not at all smooth, showing both fine-scale structure and some large spectral features which are attributable mostly to specific species, such as Ozone in the 9.6 μm region and CO_2 in the 13-18 μm range. We chose here to concentrate on the large spectral features which will allow an assessment of the underlying major radiative forcings.

The CES/NRC made very specific recommendations regarding the desired spectral decomposition: "The planetary albedo should be determined for the total solar flux as well as for the flux in several discrete, broad spectral intervals including the following minimum set: 0.3-0.5 μm , 0.5-0.7 μm , 0.7-0.9 μm , 0.9-4 μm . Furthermore, it is crucial to determine the above albedos for clear-sky conditions as well as for average cloudy conditions. It is from the clear sky values that we can discern changes in the forcing due to changes in surface properties. The measurement of the total spectrum will establish the net change in the global forcing while the spectral measurements will enable identification of the mechanism. For example, vegetation albedo is significantly (by a factor 2 to 3) lower in the 0.5- to 0.7- μm region than in the 0.9- to 4- μm region, while the snow albedo is significantly larger in the 0.5- to 0.7- μm region than in the 0.9- to 4.0- μm region. Changes in ozone will alter the albedos mainly in the 0.3- to 0.5- μm and 0.5- to 0.7- μm region." "Similar considerations apply to the long-wave flux. In addition to the integrated flux, broadband measurements are needed for the following spectral intervals: 4-7 μm , 7-13 μm , 10-13 μm ; 13-18 μm . Again, it is important to estimate clear sky values in addition to measuring average cloud conditions. The 8- to 10-K winter polar surface warming due to double CO_2 predicted by models should enhance the total outgoing flux by as much as 20 to 30 W/m^2 . The enhancement of the atmospheric greenhouse effect of CO_2 will be manifested in the 13- to 18 μm region. The cloud feedback signature will be concentrated in the 7- to 13 μm interval. Measurement of the 7- to 13 μm interval in conjunction with the 10- to 13 μm interval will help isolate the effects of ozone change (the 9.6 μm band) and volcanic aerosols, provided clear sky estimates are obtained."

Thus, our goal for coarse spectral decomposition is to achieve spectral bands which are close to those recommended by the CES.

Additionally, one wishes to make highly accurate measurements of the total radiances in the solar and thermal infra-red spectral ranges. For the solar spectrum this implies a wavelength range from 0.25 through 4 μm , while the thermal infra-red spectrum is almost fully covered by extending the wavelength range to 50 μm .

It is readily seen from satellite photographs (or, indeed, by the simple expedient of looking periodically at the sky) that cloud fields have significant short-scale structure, and that they can be highly temporally variable. One also notes that some parts of the globe (especially at high latitudes) are cloud-covered for a large fraction of the time. Since one wishes to examine cloud radiative forcing by comparing cloudy scenes to clear, one wishes to have sufficient spatial and temporal coverage to obtain a sufficient sampling. Making the instantaneous field of view (IFOV) of a radiometer smaller increases the chances of seeing homogeneous pixels, as does covering as large a total spatial domain as possible. In this context, the pixel size of GCMs is presently typically several hundred kilometers on a side, while regional models achieve pixels of some 60 kilometers^{14,15}. The desires for small pixel sizes and full spatial coverage are clearly offset by the realities of finite detector sensitivities, data handling capabilities and satellite trajectories. The resulting requirement is for nadir pixel sizes of 10-30 km, with full spatial coverage.

5. BROAD-BAND RADIOMETER - LARI

The Los Alamos Radiometric Instrument is a broad-band radiometer designed specifically to address the radiative forcing issue described in the previous sections. A sketch of the instrument design is shown in Figure 1. The particular version of LARI shown in Figure 1 is designed for use on an aircraft: an emphasis is on separating the spectral dispersion and measurement volume from the input optics which would be subject to large changes in conditions as the aircraft flies through the atmosphere. The design of a satellite version may be simpler from this standpoint, though the satellite version requires more attention to, for example, coping with large g-forces through launch.

Radiation is gathered by a cross-track scanning drum (at the lower left in Fig. 1) which contains two mirrors oriented to cancel the polarization which would result from a single 45 degree mirror system. In addition to sweeping across the scene, the scanner also accesses two on-board calibration sources, and at least one non-scene observation port, which may be used to look at space for a zero reference, or at a solar calibration system. The light is then passed through a telescope and collimated.

The light is then shared between several optical trains. Most of the light is taken through a pair of side-by-side prisms, dispersed and then focussed onto two linear array detectors. This provides contiguous coarse spectral resolution necessary to characterize the spectrum and the effects of the main contributors to the spectral shape. The detectors may be filtered if necessary to further refine spectral content. The rest of the light is also shared between two spectral channels, one of which is a completely unfiltered thermal detector which measures the whole spectrum, the other is a thermal

detector with a shortwave filter (such as suprasil) to select the whole solar spectrum. The difference between these latter two channels gives the thermal infra-red integrated radiation.

The detectors are pyroelectrics with black absorbing coatings. The coatings will be selected to be stable, and to have a uniform absorption from the ultra-violet through the infra-red: additional considerations for the coatings are that thicker (generally more absorptive) coatings will slow the time response of the detectors¹⁶.

Pyroelectric detectors have been used for many years for accurate, broad wavelength radiometry¹⁷. Pyroelectrics have also been used successfully in space applications. More recently, arrays of pyroelectric detectors with up to 100×100 elements and noise equivalent temperatures below 0.2 K have been developed¹⁸. Pyroelectric detectors respond only to changes in temperature. Therefore, the instrument measures the difference between the on-board calibration systems and the scene. This provides an absolute, contemporaneous reference for all measurements made. For a sufficiently rapid change in the scene (either endemic to the scene, or achieved though fast scanning), the incoming light can vary quickly enough to not require instrumental chopping of the light; from this perspective the chopper shown in Figure 1 could be deleted. The chopper does have some advantages, however. By providing a regular modulation, one has the ability to lock the detection electronics to a set frequency. Also, the detectors "see" the closed section of the chopper blade between each pixel measurement: so long as the thermal time constant of the chopper blade is long compared to the cross-track scan time, this provides an intermediate reference for each pixel measured. Finally, the chopper aids in calibration when using a steady-state source.

6. CALIBRATION

We first recognize that the accuracy of the final data product is the result not only of the instrument calibrations, but also of the accuracy of the models used to convert from, for example, radiance at the instrument to flux at the top of the atmosphere. Data sampling will be relatively sparse, both in space and in time, and some interpolation and extrapolation may be required. We concentrate here on the first step of the data analysis, namely taking the instrument counts and converting them to radiances at the instrument entrance apertures.

The spectral range for the calibrations is $0.25 \mu m$ through at least $50 \mu m$. The required radiometric accuracy for the integrated channels is set by the sensitivities in TOA radiances and fluxes discussed previously: the resulting calibration goal for these channels is one percent for the total channels.

Generically, the calibration requirements imply the need for a range of sources, transfer standards, detectors and environments. In the short wavelength regime, a number of sources are available, including tungsten lamps, spectral lamps, and sunlight. Sunlight is a poor calibration standard for laboratory applications, since atmospheric absorption and scattering have large and variable effects on the spectrum. The match between the spectra of the lamps and the solar spectrum tend to be poor, so that one needs to perform short-wave calibrations in a number of spectral bands. Filters, spectrometers or spectral line sources can be used to achieve this decomposition. For the LARI, the calibration is facilitated by the fact that LARI itself divides the spectrum into contiguous bands

as well as maintaining spectrally integrated channels. Other problems with the short-wave sources include very finite lifetimes of the tungsten lamps, variability of the source calibrations provided, sensitivity to operational scenarios and stability. Significant effort is needed in monitoring the sources and in frequent checking of the source outputs with reference detectors such as a cryogenic electrical substitution radiometer and 100% quantum efficiency, trapped photodiodes.

Long-wave calibration will be achieved using blackbodies. Again there is a need for several sources. One needs to cover the temperature regime from cryogenic through some 330K. Black coatings do not have flat spectral responses throughout the wide wavelength region to be covered here; blackbody spectra need to be carefully measured to allow proper calibrations. Alternatively, cavity blackbodies can be used: these compensate for non-unity emissivity of coatings by requiring multiple reflections in the source. Frequent checks of the sources against stable electrical substitution radiometers are of the essence. Again, the fact that LARI provides spectral decomposition into contiguous bands in addition to spectrally integrated channels helps in achieving a reliable calibration.

Because of atmospheric absorption effects and environmental considerations, the calibrations need to be performed in a vacuum tank and under a variety of thermal loadings on the instruments. There are documented cases of in-orbit thermal transients affecting the outputs of satellite radiometers. While LARI is less sensitive to such effects because it measures radiances with respect to the on-board calibration systems, any residual thermal effects need to be thoroughly tested and well-documented.

7. DATA PROCESSING

The conversion of instrument counts to a radiances and fluxes is a multi-step process which adds considerable uncertainty. First, consider that the radiation at the input aperture of the radiometer is not black-body; the measured counts from the instruments are the result of the convolution of the input spectrum and the spectral sensitivity of the instrument. The (admittedly coarse) spectral decomposition channels in LARI permit one to make a reasonable deconvolution to obtain spectral radiances at the instrument input aperture.

The second step is to identify some characteristics of the underlying scene. Clearly, one can use ephemeris data to determine whether the scene is, for example, over an ocean or over a desert. However, cloudiness needs to be characterized individually for each pixel, since both spatial and temporal scales for clouds are short. The first cloud characterization method discussed here is the ERBE Maximum Likelihood Estimate (MLE) method, in which one divides scenes into several cloudiness ranges based on the relative emissions in the integrated shortwave and longwave channels¹⁹. A second method is based on the ratio of the broad-band visible/near-infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) and summing over the many ≥ 1 -km AVHRR pixels which fill an ERBE pixel²⁰. Significant differences are seen in these two methods of scene identification, with some 30 percent of scenes being classified in a different category by the two methods (almost all of these are one-category differences). The result of these misidentifications on the computed TOA short-wave exitances are as high as $14 \text{ W} \cdot \text{m}^{-2}$; longwave exitance errors

are much smaller. The LARI instrument bands includes two broad spectral bands which essentially overlap the AVHRR channels 1 and 2. Thus, both of these scene identification algorithms can be employed from LARI data to reduce the number of scene mis-identifications. (Other scene identification algorithms have also been developed, and may be used.)

The final step in converting from instrument radiances to TOA exitances requires a knowledge of the bi-directional reflectivity functions (BRDF), which are scene dependent. A database of Nimbus observations of the BRDF is used in the ERBE analysis; further BRDF data will be obtained from the rotating aperture plane scanner on the CERES radiometers to be flown late in this decade. Thus BRDF remains a major source of uncertainty in the computation of TOA exitances from instrument radiances (and *vice versa*).

7. SUPPLEMENTARY INFORMATION

As discussed, the LARI instrument has a number of useful attributes for radiative forcing studies. These include accurate measurements of the solar and total radiances, and spectral decomposition which gives the radiative forcing from major contributors, and also provides alternative scene identification methods.

Since the major radiative forcing variability is due to clouds, it is appropriate to consider additional remote sensing of cloud properties (beyond the classification of scenes as clear, partly cloudy, mostly cloudy or overcast). For example, the reflection function at $0.75 \mu m$ is primarily sensitive to cloud optical thickness, whereas the reflection function at $2.16 \mu m$ is sensitive primarily to the effective droplet radius. (Note that for thin clouds these spectral measurements may not yield a unique solution²¹. An aircraft-borne experiment based on these methods and with comparisons to in-situ sampling has been reported²². Systematic differences exist between the remotely sensed and in-situ results, possibly due to anomalous gaseous absorption at the $2.16 \mu m$ wavelength.

A spectrometer designed to examine a dozen spectral lines of interest to cloud parameter determinations has been proposed²³.

8. SUMMARY

An examination of atmospheric radiative forcing has been presented, with an emphasis on the possibility of testing models with a self-consistent, sufficiently complete, but compact set of measurements. The methodology relies on measuring atmospheric parameters (temperature, humidity, clouds, ...) to accuracies which translate linearly to equivalent flux changes of less than $10 W \cdot m^{-2}$ at the top of the atmosphere. The measurement of TOA broadband radiances is then used as a diagnostic for model testing and verification. Since cloud forcing is a large factor, one needs to design the coverage of the experiment to ensure both clear sky pixels and a variety of relatively homogeneous cloudy pixels. This, coupled with the resolution capabilities of models, leads to the choices of spatial resolution and full spatial coverage.

Radiances in broad spectral bands, plus totals, would be obtained from the LARI instrument, together with improved scene identification capabilities. The coarse spectral decomposition in LARI shows the major radiative forcing contributions (CO_2 , O_3 , scattering,...).

Temperature and humidity data need to be obtained in all weather conditions, implying the need for microwave instrumentation, which tends to require too many resources for a small satellite. Fortunately, the scale-lengths are sufficiently long to permit using measurements from operational weather satellites for the present study.

Additional cloud properties may be obtained from the addition to the payload of a spectrometer with a dozen or so well-selected narrow spectral bands.

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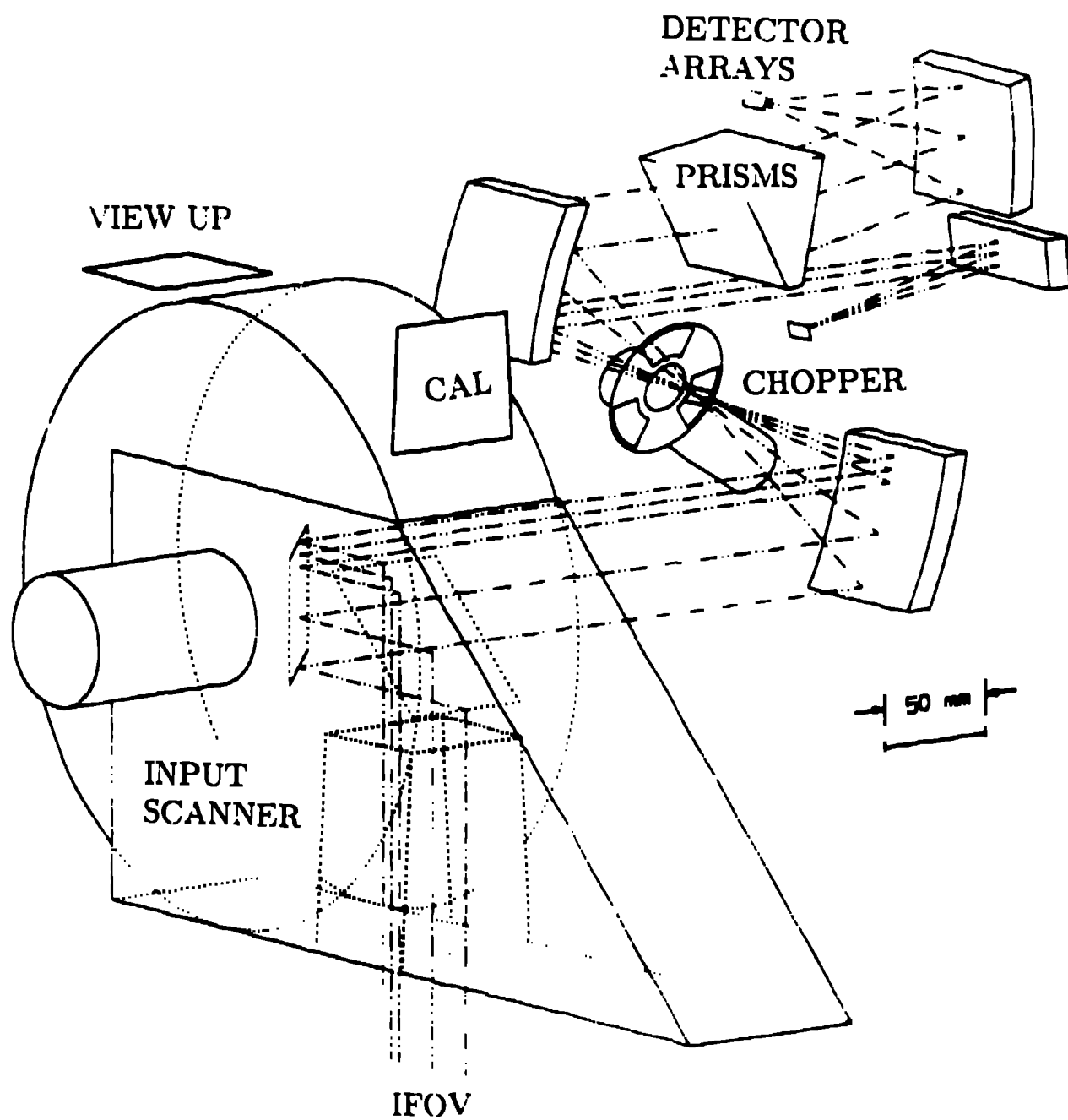


Fig. 1: Broad band radiometer schematic.